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# European Trend Atlas of Extreme Temperature and Precipitation Records

Springer

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# Preface

Climate change not only includes changes in mean conditions, but also covers changes in extremes. For impact on society, extreme climatic conditions are often much more important than mean climate. Thus adaptation to climate change needs to take historical changes in the extreme climatic conditions into account. Europe is one of a few places in the world where the longest instrumental meteorological records exist, which provides an important opportunity to reveal long term changes in the extremes. Over the past decade, several research projects at the European level have dealt with changes in extreme climatic conditions in Europe.

One of these projects is EMULATE (European and North Atlantic daily to MULtidecadal climATE variability) that was supported by the European Commission under the Fifth Framework Programme. The project contributed to the implementation of the Key Action "Global change, climate and biodiversity" within the Environment, Energy and Sustainable Development. It was coordinated by Prof. Phil Jones, Climatic Research Unit at the University of East Anglia, UK and had eight participating institutions across Europe. One of the outcomes of the EMULATE project was a systematic mapping of the observed trends of 64 temperature and precipitation indices based on daily instrumental records in Europe. The majority of the indices describe extreme climatic conditions.

In 2006, this systematic mapping was published as an internal report at the University of Gothenburg, which was one of the participating organizations of EMULATE. However, given the nature of the report, the accessibility is limited. Over recent years, needs for information about past changes in extreme climatic conditions have significantly increased. This is particularly true for really extreme conditions and for extended time perspectives. This in 2012, the authors of the report decided to publish an atlas of those indices that represent the most extreme conditions of climate in Europe. This idea resulted in an atlas attempting to show a subset of all the EMULATE indices to a much wider audience than the internal report does.

This atlas presents information in the form of maps, time series and tables for a selection of 27 indices. Four of them represent mean climate conditions while the remaining indices represent climate extremes. All indices were derived from daily temperature and precipitation data at European meteorological stations with records starting before 1901. Since the updating of the daily records for the stations after 2000 has not been finished, this atlas was prepared by using the trends only until 2000 for all the stations. Seasonal trends of the indices during three periods (1801–2000, 1851–2000, and 1901–2000) were shown and their significance was tested. The stations for 1901–2000 were also grouped into three regions (Northern, Central, and Southern Europe) and regional means were calculated. The trend which this atlas provides is an easy way to show spatial patterns for a given time period, region, season, and index. There is strong evidence that climate in Europe has changed during the three periods analyzed, such that the occurrence and intensity of warm temperature extremes have increased. Precipitation extremes have also changed, but with a less clear pattern compared to the temperature extremes.

The atlas should be interesting to and useful for researchers who are from or interested in Earth and Environmental Sciences and practitioners from many sectors in society who are concerned with climate changes in the mean and extreme conditions in Europe.

On behalf of the writing team, I would like to express our thanks to the European Commission for their financial support to EMULATE with the contract EVK2-CT-2002-00161. The Swedish Research Council and the Swedish Rescue Services Agency are thanked for their support and grants. Dr. Elodie J. Tronche and Mariëlle Klijn from Springer are acknowledged for their support and understanding throughout the preparation of the atlas.

Gothenburg Deliang Chen
October 2013

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# 1 Introduction

The impact of climate change on society is of fundamental importance for future planning and management. Statistics of extreme events is considered as a part of the climate, and their changes often have much higher impact on society than changes in the mean climate. As the mean climate changes, the characteristics of extremes may also change (e.g. Trenberth 1999; Easterling et al. 2000; Beniston and Stephenson 2004). For many impact applications and decision support systems, extreme events are much more important than the mean climate (e.g. Mearns et al. 1984; WISE 1999). Changes in extremes may be due to changes in the mean (Wigley 1985), changes in the variance (Katz and Brown 1992), or a combination of both factors (e.g. Brown and Katz 1995; Beniston 2004).

Extreme climate events can be defined as events that occur with extraordinary low frequency during a certain period of time (rarity), events with high magnitude (intensity) or duration, and events causing sizeable impacts such as direct damages to assets, cultural heritage, ecosystem service and loss of human lives. According to The Intergovernmental Panel on Climate Change (IPCC) (IPCC 2001, p. 790), "An extreme weather event is an event that is rare within its statistical reference distribution at a particular place. Definitions of 'rare' vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile. By definition, the characteristics of what is called extreme weather may vary from place to place. An extreme climate event is an average of a number of weather events over a certain period of time, an average which itself is extreme (e.g. rainfall over a season)." This definition has also been used in the fourth IPCC report published in 2007 (IPCC 2007).

Indices have been developed to measure the degree of exceedance of specific thresholds (which define the rarity of such an event) for maxima/minima during specific time-periods (Jones et al. 1999). Examples are the number of very warm and very cold days for the time of year, the number of heavy rainfall days, and number of frost days (Frich et al. 2002). Some extremes are defined by natural thresholds, while the majority of extremes are determined by the data's own distribution. The majority of indices relate to counts of individual daily extremes, but a few are determined by spells of exceptionally warm/cold temperatures or wet/dry periods or the first/last occurrence of an event during a season (like spring/autumn frosts, beginning/end of the summer dry season etc.). With respect to temperature and rainfall, spells of extreme weather generally have large societal and economic impacts. Examples of short-lived extremes that may cause extensive damage are windstorms, hailstorms and extensive and heavy snowfall.

Recently, there has been an international effort towards developing a suite of standardized indices so that researchers around the world can calculate the indices in exactly the same manner. This is important for detecting and monitoring changes in the extreme climates and allows for comparison of observations and model simulations at the global scale. These analyses can then be combined into the regional and global perspectives (Karl and Easterling 1999; Peterson et al. 2001; Frich et al. 2002). However, the definition of several of the suggested indices is somewhat cumbersome and some of the indices still exist in various forms. Consequently, different software may produce slightly different results. Several EU research projects either use the indices in the European Climate Assessment (Klein-Tank et al. 2002a; Klein-Tank and Können 2003) or a program developed within the STARDEX project (STAtistical and Regional dynamical Downscaling of EXtremes for European regions; Haylock and Goodess (2004)). In this atlas we use the extremes indices software developed within EMULATE (European and North Atlantic daily to MULtidecadal climATE variability; Moberg et al. (2006)).

While some of the climatic extremes are well described by meteorological variables/indices, others may not be easily defined with data for a single meteorological variable only. This is true when the combined impact is involved (Pellikka and Järvenpää 2003). For example, freezing rain is a special combination of low temperature and rain that produces major damages through ice loading on wires and structures. Other examples are snow damage on forests (Solantie 1994) and

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the occurrence of landslides that are known to be caused by heavy rains (e.g. Schuster 1996). However, geological and geomorphologic settings may also play an important role here (Brunsden 1999). Yet another type of climate extreme is that some weather conditions, which may seem more or less normal from a purely anthropocentric perspective, nevertheless could induce a strong impact on some other species. Thus, such ecological climate extremes may not be easy to identify as climate extremes. The dependence on factors other than meteorological data makes it difficult to disentangle the specific contribution of weather/climate in producing the impacts and to describe the combination of extremes. A possible solution to this problem is interactions with affected and interested groups and individuals, such as the insurance industry and design engineers.

Damage reports from (re)insurance companies may also be useful. Nevertheless, since there is no long-term homogeneous data yet in this regard, the use of this approach in climate change studies is not feasible at this point. Therefore, this atlas will not discuss these kinds of extremes. Rather, the focus will emphasize a set of indices well defined by meteorological data that are available for relatively long time periods, i.e. temperature and precipitation.

While an increasing number of climate model studies indicate that rising contents of greenhouse gases in the atmosphere will probably lead to more severe weather conditions in the future, it is of great importance to increase our understanding regarding the occurrence of climate extremes in the recent and more remote past. During recent years, a large number of studies have been carried out focusing on various aspects of climate extremes (mainly temperature and precipitation) in different regions of the world (e.g. Trenberth 1999; Easterling et al. 2000; Beniston and Stephenson 2004). Depending on research tasks, different measures were used to quantify extremes, but which do not always allow direct comparison of results. A general conclusion of many of these studies is, however, that changes in extreme temperature and precipitation have occurred world-wide during the past century along with the ongoing climate change in terms of the mean temperature (Donat et al. 2013). Yet, it is still hard to draw a firm conclusion from these studies concerning the extent to which these changes are due to natural variability or caused by anthropogenic activity (IPCC 2007; Field et al. 2012), although more recent studies indicate that increase in extreme events is indeed linked to man-made global warming (Hansen et al. 2012).

In an attempt to summarize the changes around the globe, Groisman et al. (1999) and Groisman et al. (2005) studied the probability distribution of daily precipitation in eight countries located on different continents and concluded that increased mean precipitation is associated with an increase in heavy rainfalls. In their near-global analysis, Frich et al. (2002) found regions with both negative and positive changes in extremes, with parts of Europe having more robust positive changes. Using extremes indices similar to some of those produced by the EMULATE project, Moberg and Jones (2005) investigated trends in daily temperature and precipitation extremes across Europe over the past century and found that both mean and extreme precipitation have increased mainly during winter. Also Klein-Tank and Können (2003) found an increase in the annual number of moderate and very wet days between 1946 and 1999.

Several studies have also been carried out at the national level. Fowler and Kilsby (2003) studied multi-day rainfall events in the UK since 1961 and found significant but regionally varying changes in the 5- and 10-day events, which they consider as having important implications for the design and planning of flood control measures. In Central Europe, Schmidli and Frei (2005) found significant increasing trends in winter and autumn rainfall in Switzerland and Hundecha and Bárdossy (2005) found increasing precipitation extremes across western Germany since 1958. The increase in Central European daily precipitation beyond the 98th percentile has occurred during all seasons except summer (Jacobeit et al. 2009). In northern Europe, Achberger and Chen (2006) studied the spatial patterns and long-term trends of precipitation indices in Sweden and Norway on an annual and seasonal basis for the years 1961 to 2004. These indices are based on daily data from 471 stations. Analysis of the trends of the various indices for the period 1961–2004 shows that the magnitude and sign of the trends varies depending on index, region and season. A clear majority of stations show increasing trends, though the fraction having statistically significant trends is small. In Norway, positive trends are most common during winter, while at Swedish stations, positive trends are most frequent in spring and summer. Autumn has the highest number of stations in both countries with negative trends. The findings are generally in line with results from other studies concluding that regions at middle and higher latitudes are becoming wetter and extreme temperatures and precipitation are becoming more frequent and more intense.

The importance of monitoring and analyzing climate extremes has been highlighted by the past assessment reports of the IPCC, and during a special IPCC meeting on climate extremes held in Beijing in June 2002 (Houghton et al. 2002). Since then, there has been increased research around the world, particularly in the US and European countries, that aims at a better understanding of the observed extremes (e.g. Arndt et al. 2010), detection and attribution of extremes (e.g. Christidis et al. 2005; Morak et al. 2011; Zwiers et al. 2011), factors that influence extremes (e.g. Haylock and Goodess 2004; Vautard and Yiou 2009; Zhang et al. 2010), and interpretation of observed extremes in a climate context (e.g. Peterson et al. 2012). In 2012 IPCC published a Special Report on Extremes (Field et al. 2012) which summarized and assessed studies with regard to changes in climate

Extremes and their Impacts on the natural physical environment and human systems and ecosystems, as well as managing the risks from climate extremes at the Local Level round the world.

Instrumental data sets enabling studies of changes in extreme climate events in Europe have been collected by ECA&D (European Climate Assessment and Dataset) (Klein-Tank et al. 2002b), and by the STARDEX project (Haylock and Goodess 2004). This atlas represents an effort within the EMULATE project. The EMULATE project partly built on the ECA&D data set, but also on European station data from other projects and data obtained through direct contacts with several national weather services and additionally presented a set of newly digitized and collected daily data at many Spanish stations (Moberg et al. 2006). While the analysis in Moberg et al. (2006) focused on a rather small subset of all the indices (19 out of 64) during only the summer and winter seasons within the period 1901–2000, Chen et al. (2006) presented results for all the 64 indices for all seasons and three different time periods. The focus of this new atlas is on a systematic trend analysis of a subset of 27 out of the 64 indices that together represent the most extreme climatic conditions for all seasons and also climatic mean conditions for comparison. The trends at individual stations are presented for the periods 1801–2000, 1851–2000, and 1901–2000. Results for the latter period are also aggregated into three sub-regions of Europe (Northern, Central, and Southern Europe).

This study is motivated by the need for easy access to information about changes in the extreme climatic conditions at the European meteorological stations with the longest daily records. This need is becoming more and more important as adaptation work in response to climate change has being implemented in Europe. The report is organized as follows. Chapter 2 describes the data and method used. Chapter 3 presents the results of the trend analysis for all the selected indices, stations and regions in maps and figures. Some statistics for the stations and regions are developed in Chapter 4 to summarize these results in tabular form. Finally, Chapter 5 provides the conclusions that summarize the information shown by the tables and figures. The appendix lists all estimated seasonal trends for all the indices at all stations as a quick overview.

# Data & Methods

# 2

The methods used in this study follow those used by Moberg et al. (2006) and Chen et al. (2006). A brief description is given below, while detailed information can be found in these references, except for the regional division used here. For the regional analysis, we followed the regional divisions used by the recent IPCC special report (IPCC 2012), rather than the approach used by Moberg et al. (2006) and Chen et al. (2006).

EMULATE collected a dataset containing daily temperature and precipitation observations over European locations having data starting before 1901. This dataset is the basis for the analyses in this atlas. Up to four daily climate variables are available: minimum and maximum temperature (Tmin/Tmax), mean temperature (Tmean), and precipitation (Prec). We focus on three periods: 1801–2000, 1851–2000, and 1901–2000. Since a trend analysis is extremely sensitive to the starting and ending of the time series, particular attention is paid to the missing data in these beginning and ending periods. A data completeness criterion has been applied to filter out stations with insufficient data for the proposed analyses. We divided each analysis period in question into three sub periods: one 20-year period at the beginning, one 20-year period at the end of the series and the entire period in between (160, 110, or 60 years according to the period analyzed). A station passed the filter if it did not have more than 4% of missing values in the two 20 year blocks at the beginning and end and at most 6% missing values in the longer block in between. All the stations that passed the criterion and are used in this work are listed in Table 2.1 and shown in Figs. 2.1, 2.2 and 2.3.

For the 200-year period (1801–2000) we can use only three stations with Tmin/Tmax, and seven stations with Tmean measurements. No precipitation observations are available for this period. Looking at the 150-year period (1851–2000) the number of observations is increased to nine for Tmin/Tmax, thirteen for Tmean, and nine for precipitation. For these two periods the analyses were carried out for each station with sufficient data. The number of stations for these two periods is too few to undertake any averaging or regionalization approaches. For the 100-year period (1901–2000) significantly more stations are available: we have 57 observation sites for Tmin/Tmax, 54 for Tmean, and 100 for Precipitation. The stations are fairly unevenly distributed over the study area, although we find the highest station density in Central Europe. The relatively high number of observation sites for this period provides the possibility to group the stations into regions, which enables a regional analysis and inter comparison between regions.

Using regional divisions for the regional analysis facilitates direct comparison of the regional trends with other estimates and model simulations. As indicated in Figs. 2.1, 2.2 and 2.3, the following three regions were created: NEU (Northern Europe), CEU (Central Europe), and SEU (Southern Europe).

The climate indices described in the next section were computed for all stations belonging to a particular region. Afterwards the time series have been averaged arithmetically. The resulting averaged time series was taken as the regional mean and was subject to a linear trend analysis over the whole 100-year period.

The quality of the station series selected for this study varies. All series have been corrected for obvious errors whereas efforts towards homogenizing the database could not be undertaken. Relatively few series have undergone intensive testing and correction for inhomogeneities, among them the very long records for some Swedish stations (Moberg and Bergström 1997). Some of the series have been used more frequently than others in the literature and are in this context also more quality controlled. We have to keep in mind that inhomogeneous data can cause errors in estimated trend values as demonstrated by Venema et al. (2012). In particular with respect to the method of linear regression, which is more sensitive to values at the beginning and end of the respective time series analyzed for linear trend. During the recent past substantial efforts have been undertaken to improve the availability and quality of long-term climate observations. For example, 557 monthly long-term observation series for the Greater Alpine Region where collected,

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**Table 2.1** Data availability for the three groups of observation at the meteorological stations used

| ID | Lat | Lon | Station | Country | Tmin/Tmax | Tmean | Prec |
|---|---|---|---|---|---|---|---|
| 1 | 48.08 | 15.45 | Graz university | Austria | *x* | *x* | *x* |
| 2 | 47.27 | 11.40 | Innsbruck university | Austria | *x* | *x* | *x* |
| 3 | 48.05 | 14.13 | Kremsmünster | Austria | *x* | *x* | *x* |
| 4 | 47.80 | 13.00 | Salzburg | Austria | *x* | *x* | *x* |
| 5 | 47.05 | 12.95 | Sonnblick | Austria | *x* | *x* | *x* |
| 6 | 48.23 | 16.35 | Wien | Austria | *x* | *x* | *x* |
| 7 | 50.90 | 4.53 | Brussels-Uccle | Belgium | *x* | *x* | *x* |
| 8 | 43.85 | 18.38 | Sarajevo | Bosnia | *x* | *x* | *x* |
| 9 | 45.17 | 14.70 | Crikvenica | Croatia |  | *x* |  |
| 10 | 45.82 | 15.98 | Zagreb | Croatia | *x* | *x* | *x* |
| 11 | 50.08 | 14.42 | Prag | Czech | *x* | *x* | *x* |
| 12 | 55.28 | 14.78 | Hammer odde fyr | Denmark | *x* | *x* | *x* |
| 13 | 55.45 | 8.40 | Nordby | Denmark | *x* | *x* | *x* |
| 14 | 55.85 | 10.60 | Tranebjerg | Denmark | *x* | *x* | *x* |
| 15 | 56.77 | 8.32 | Vestervig | Denmark | *x* | *x* | *x* |
| 16 | 60.32 | 24.97 | Helsinki | Finland | *x* | *x* | *x* |
| 17 | 43.31 | 5.40 | Marseille | France | *x* | *x* | *x* |
| 18 | 48.82 | 2.34 | Paris parc montsouris | France | *x* | *x* | *x* |
| 19 | 49.88 | 10.88 | Bamberg | Germany | *x* | *x* | *x* |
| 20 | 52.45 | 13.30 | Berlin | Germany | *x* | *x* | *x* |
| 21 | 53.03 | 8.78 | Bremen | Germany | *x* | *x* | *x* |
| 22 | 48.73 | 9.72 | Göppingen | Germany |  |  | *x* |
| 23 | 49.28 | 9.17 | Gundelsheim | Germany |  |  | *x* |
| 24 | 53.48 | 10.25 | Hamburg-Bergedorf | Germany | *x* | *x* | *x* |
| 25 | 53.55 | 9.97 | Hamburg-Fuhlsbüttel | Germany | *x* | *x* | *x* |
| 26 | 53.15 | 11.03 | Hitzacker | Germany |  |  | *x* |
| 27 | 47.80 | 11.00 | Hohenpeissenberg | Germany | *x* | *x* | *x* |
| 28 | 48.42 | 8.67 | Horb-Betra | Germany |  |  | *x* |
| 29 | 47.68 | 10.05 | Isny | Germany |  |  | *x* |
| 30 | 50.93 | 11.58 | Jena | Germany | *x* | *x* | *x* |
| 31 | 49.03 | 8.35 | Karlsruhe | Germany | *x* | *x* | *x* |
| 32 | 49.20 | 8.10 | Landau/Pfalz | Germany |  |  | *x* |
| 33 | 48.85 | 12.92 | Metten | Germany |  |  | *x* |
| 34 | 48.17 | 11.50 | Muenchen | Germany | *x* | *x* | *x* |
| 35 | 49.22 | 9.52 | Oehringen | Germany |  |  | *x* |
| 36 | 52.38 | 13.07 | Potsdam | Germany | *x* | *x* | *x* |
| 37 | 48.72 | 9.22 | Stuttgart | Germany | *x* | *x* | *x* |
| 38 | 48.02 | 8.82 | Tuttlingen | Germany |  |  | *x* |
| 39 | 47.87 | 11.78 | Valley-Mühltal | Germany |  |  | *x* |
| 40 | 53.78 | 7.90 | Wangerooge | Germany |  |  | *x* |
| 41 | 52.90 | 8.43 | Wildeshausen | Germany |  |  | *x* |
| 42 | 47.42 | 10.98 | Zugspitze | Germany | *x* | *x* | *x* |
| 43 | 37.97 | 23.72 | Athens | Greece | *x* | *x* | *x* |
| 44 | 65.08 | −22.73 | Stykkisholmur | Iceland |  | *x* | *x* |
| 45 | 53.37 | −6.35 | Dublin | Ireland |  |  | *x* |
| 46 | 44.48 | 11.50 | Bologna | Italy | *x* | *x* | *x* |
| 47 | 44.82 | 11.50 | Ferrara | Italy |  |  | *x* |
| 48 | 45.15 | 10.75 | Mantova | Italy |  |  | *x* |
| 49 | 45.50 | 9.20 | Milano | Italy | *x* | *x* | *x* |
| 50 | 38.11 | 13.36 | Palermo | Italy |  |  | *x* |
| 51 | 45.38 | 10.87 | Verona-Villafranca | Italy |  |  | *x* |

**Table 2.1** (continued)

| ID | Lat | Lon | Station | Country | Tmin/Tmax | Tmean | Prec |
|---|---|---|---|---|---|---|---|
| 52 | 52.10 | 5.18 | De Bilt | Netherlands | *x* | *x* | |
| 53 | 52.97 | 4.76 | De Kooy | Netherlands | | | *x* |
| 54 | 53.13 | 6.58 | Eelde | Netherlands | | | *x* |
| 55 | 53.18 | 6.60 | Groningen | Netherlands | | | *x* |
| 56 | 52.40 | 6.05 | Heerde | Netherlands | | | *x* |
| 57 | 52.31 | 4.70 | Hoofddorp | Netherlands | | | *x* |
| 58 | 52.64 | 5.07 | Hoorn | Netherlands | | | *x* |
| 59 | 51.68 | 3.86 | Kerkwerve | Netherlands | | | *x* |
| 60 | 51.57 | 4.53 | Oudenbosch | Netherlands | | | *x* |
| 61 | 51.18 | 5.97 | Roermond | Netherlands | | | *x* |
| 62 | 52.88 | 7.06 | Terapel | Netherlands | | | *x* |
| 63 | 53.37 | 5.22 | West-Terschelling | Netherlands | | | *x* |
| 64 | 51.98 | 6.70 | Winterswijk | Netherlands | | | *x* |
| 65 | 60.65 | 6.22 | Bulken | Norway | | | *x* |
| 66 | 59.12 | 11.38 | Halden | Norway | | | *x* |
| 67 | 63.22 | 11.12 | Lien I Selbu | Norway | | | *x* |
| 68 | 38.72 | −9.15 | Lisboa Geofisica | Portugal | *x* | *x* | |
| 69 | 44.42 | 26.10 | Bucuresti | Romania | | | *x* |
| 73 | 51.65 | 36.18 | Kursk | Russia | | *x* | *x* |
| 77 | 59.97 | 30.30 | St Petersburg | Russia | *x* | *x* | *x* |
| 79 | 38.37 | −0.50 | Alicante | Spain | *x* | *x* | *x* |
| 80 | 38.88 | −6.83 | Badajoz | Spain | *x* | *x* | *x* |
| 81 | 42.36 | −3.72 | Burgos | Spain | | | *x* |
| 82 | 36.50 | −6.23 | Cadiz | Spain | *x* | *x* | |
| 83 | 37.14 | −3.63 | Granada | Spain | *x* | *x* | *x* |
| 84 | 40.41 | −3.68 | Madrid | Spain | *x* | *x* | |
| 85 | 37.98 | −1.12 | Murcia | Spain | *x* | *x* | *x* |
| 86 | 37.42 | −5.90 | Sevilla | Spain | | | *x* |
| 87 | 41.44 | −2.48 | Soria | Spain | *x* | *x* | *x* |
| 88 | 41.64 | −4.77 | Valladolid | Spain | *x* | *x* | *x* |
| 89 | 60.62 | 15.67 | Falun | Sweden | *x* | *x* | *x* |
| 90 | 65.07 | 17.15 | Stensele | Sweden | *x* | | *x* |
| 91 | 59.35 | 18.05 | Stockholm | Sweden | *x* | *x* | |
| 92 | 59.87 | 17.63 | Uppsala | Sweden | *x* | *x* | *x* |
| 93 | 56.87 | 14.80 | Växjö | Sweden | *x* | | *x* |
| 94 | 47.55 | 7.58 | Basel | Switzerland | *x* | *x* | *x* |
| 95 | 46.93 | 7.42 | Bern | Switzerland | *x* | *x* | *x* |
| 96 | 47.05 | 6.99 | Chaumont | Switzerland | | | *x* |
| 97 | 46.25 | 6.13 | Geneva | Switzerland | *x* | *x* | *x* |
| 98 | 46.00 | 8.97 | Lugano | Switzerland | *x* | *x* | *x* |
| 99 | 47.25 | 9.35 | Säntis | Switzerland | *x* | *x* | *x* |
| 100 | 46.23 | 7.37 | Sion | Switzerland | | *x* | *x* |
| 101 | 47.38 | 8.57 | Zurich | Switzerland | *x* | *x* | *x* |
| 102 | 54.35 | −6.65 | Armagh | UK | *x* | | *x* |
| 103 | 52.20 | 0.13 | Cambridge | UK | | | *x* |
| 104 | 52.42 | −1.83 | CET | UK | *x* | *x* | |
| 105 | 51.77 | −1.27 | Oxford | UK | *x* | | *x* |
| 106 | 58.33 | −6.32 | Stornoway | UK | *x* | | |
| 107 | 45.03 | 35.38 | Feodosija | Ukraine | *x* | | *x* |
| 108 | 50.40 | 30.45 | Kiev | Ukraine | *x* | *x* | *x* |
| 109 | 49.60 | 34.55 | Poltava | Ukraine | *x* | *x* | |

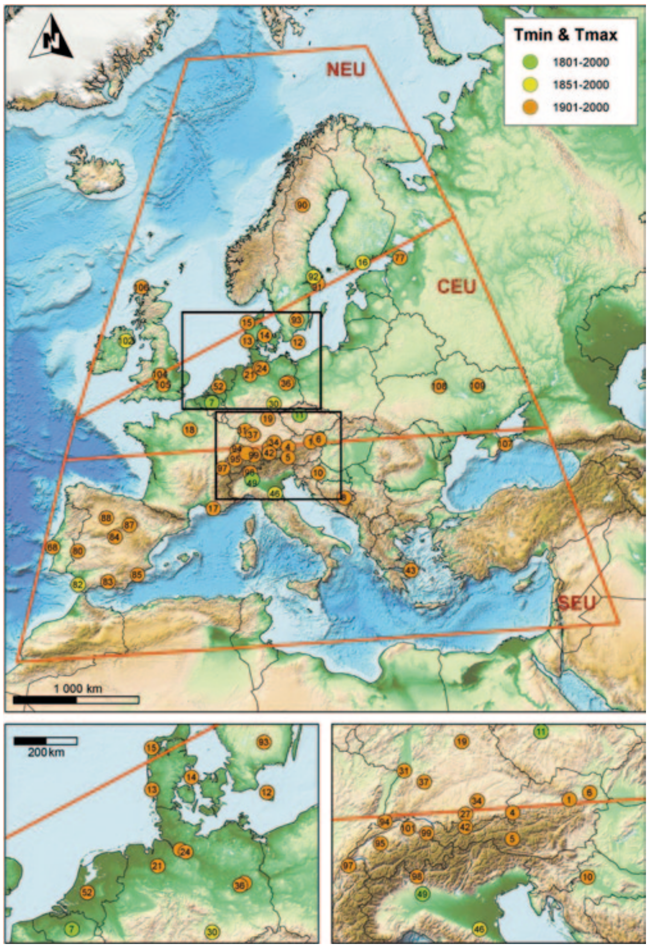

**Fig. 2.1** Overview map showing the meteorological Tmin and Tmax observations used for each period and the regional division used for the period 1901–2000

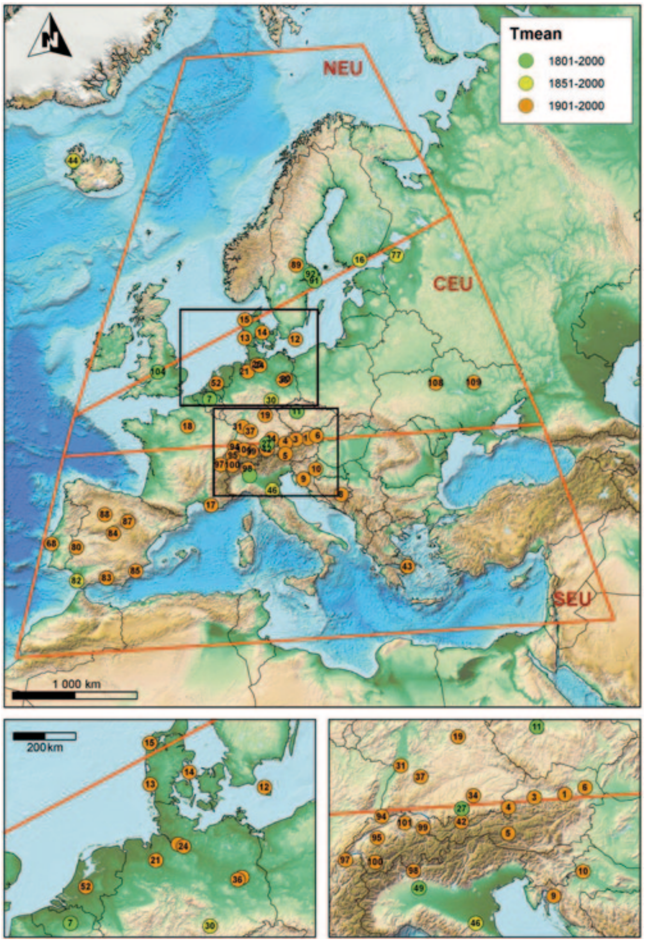

**Fig. 2.2** Overview map showing the meteorological Tmean observations used for each period and the regional division used for the period 1901–2000

quality controlled and homogenized within the HISTALP project (Auer et al. 2007). There is an obvious need for increased resources and efforts going into further developing homogenization methods in order to improve data quality especially for observations with temporal resolution higher than monthly, last but not least with respect to climatology beyond mean conditions. Brunet and Jones (2011) estimate that about 80 % of past climate data is still unavailable to the research community hampering a more robust assessment of climate parameters.

## 2.1 Climate Indices Calculated

All the selected indices have been computed for each of the three periods described above. Typically there was one value per season per index comprising the index timeseries (100, 150 or 200 years) which was then used for the trend estimation. The indices are listed and explained in Table 2.2. Most indices are either percentiles or percentile-based. With percentiles the most extreme values in both tails of

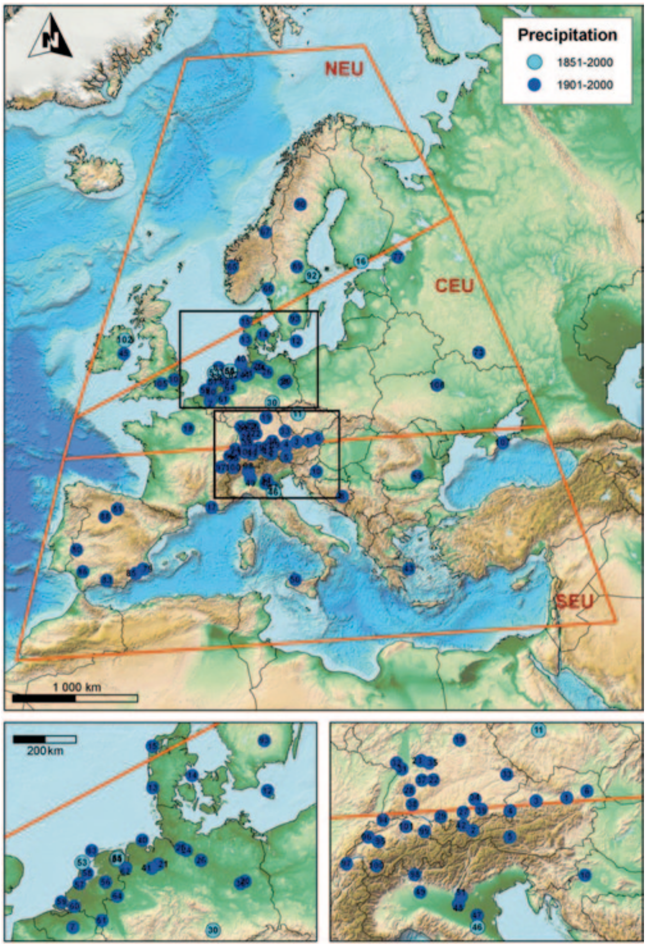

**Fig. 2.3** Overview map showing the meteorological precipitation observations used for each period and the regional division used for the period 1901–2000

the frequency distribution of a variable can be captured. For example, the 2 % highest values exceed the 98th percentile. Some indices use thresholds calculated for a reference period to be exceeded or fallen below. For those 1961–1990 was used as reference. For the temperature variables both the 2nd and 98th percentile were chosen in order to capture extremely cold and warm conditions, whereas for precipitation only the 98th percentile was utilized. In the literature the usage of 1st/99th percentile (instead of 2nd and 98th) is more common. However, using somewhat lower thresholds can yield more robust results. The index time series to deal with are relatively short, e.g. one index value per season yields 150 values for the 150-year period. In this way three values exceed the threshold (98th) instead of one (99th). Considering the characteristics of extremes connected to issues related to data quality this can be a useful measure.

Not all the indices are real extremes indices. Some of them represent mean conditions to make it possible to illustrate similarities and differences between changes in extremes and in mean conditions. In addition to the mean indices, the following indices are not based on percentiles. The Heat Wave Duration Index (HWDI), daily precipitation intensity indices (SDII98 and SDII), highest 5-day total rainfall (R5d), highest daily rainfall (R1d) and the highest number of consecutive dry days (CDD).

All indices were computed separately for each of the 3-month seasons (MAM = March–May, JJA = June–August, SON = September–November, and DJF = December–February). Further details on the indices used can be found in Moberg et al. (2006) and Beniston et al. (2007).

### 2.1.1 Trend Analysis

The ordinary least squares method was used to estimate linear trends of the temperature and precipitation indices. The trend was computed for each particular period in question: 200 years, 150 years, and 100 years. For easy comparison among different periods, all trends were given in *unit/100years*. The significance of a particular trend estimated was determined by a t-test on the estimated slope of the regression as done in Moberg et al. (2006). The lag-1 autocorrelation in each series has been taken into account to adjust the degrees of freedom accordingly. Trends that are determined to be significant at the 5 and 1 % level were flagged in diagrams and tables that present the results.

**Table 2.2** Extremes indices calculated

| # | Variable | Identifier | Parameter | Unit |
|---|---|---|---|---|
| 1 | *Tmin/Tmax* | MEANTN | Mean Tmin | °C |
| 2 | | MEANTX | Mean Tmax | °C |
| 3 | | TN2P | Tmin 2nd percentile | °C |
| 4 | | TN98P | Tmin 98th percentile | °C |
| 5 | | TN2N | [a]# of days below the reference 2nd Tmin percentile | [days] |
| 6 | | TN98N | [a]# of days exceeding the reference 98th Tmin percentile | [days] |
| 7 | | CSDI10 | [b]Cold spell duration index | [days] |
| 8 | | TX2P | Tmax 2nd percentile | °C |
| 9 | | TX98P | Tmax 98th percentile | °C |
| 10 | | TX2N | [a]# of days below the reference 2nd Tmax percentile | [days] |
| 11 | | TX98N | [a]# of days exceeding reference 98th Tmax percentile | [days] |
| 12 | | WSDI90 | [c]Warm spell duration index | [days] |
| 13 | | HWDI | [d]Heat wave duration index | [days] |
| 14 | *Tmean* | MEANTG | Mean Tmean | °C |
| 15 | | TG2P | Tmean 2nd percentile | °C |
| 16 | | TG98P | Tmean 98th percentile | °C |
| 17 | | TG2N | [a]# of days below reference 2nd Tmean percentile | [days] |
| 18 | | TG98N | [a]# of days exceeding reference 98th Tmean percentile | [days] |
| 19 | *Precipitation* | PRECTOT | Precipitation total | [mm] |
| 20 | | PREC98P | Precipitation 98th percentile | [mm] |
| 21 | | R98N | [a]# of days exceeding reference 98th precipitation percentile | [days] |
| 22 | | R98T | Fraction of precipitation above the reference 98th precipitation percentile | [%] |
| 23 | | SDII98P | Daily rainfall intensity of rainfall events above 98th reference precipitation percentile | [mm] |
| 24 | | SDII | Simple daily rainfall intensity index | [mm] |
| 25 | | R5d | Greatest 5-day total rainfall | [mm] |
| 26 | | R1d | Greatest daily total rainfall | [mm] |
| 27 | | CDD | max # of consecutive dry days (<1 mm) | [days] |

[a] Reference percentile based on 1961–1990

[b] CSDI10: Cold Spell Duration Index. Counted are the total number of at least 6 consecutive days with Tmin below long-term 10th percentile (1961–1990)

[c] WSDI90: Warm Spell Duration Index. Counted are the total number of at least 6 consecutive days with Tmax exceeding long-term 90th percentile (1961–1990)

[d] HWDI: Heat Wave Duration Index ($Tx_{ij} > Tx_{inorm} + 5$). Let Txij be the daily maximum temperature at day *i* of period *j*. Let $Tx_{inorm}$ be the calendar day mean calculated for a 5 day window centered on each calendar day during the base period (1961-1990).Then counted are the total number of spells of at least 6 consecutive days exceeding $Tx_{inorm}+5$ °C

# 3

# Atlas of the Trend Analysis

In this chapter, the results of the trend analysis for each index, station or region are presented in the form of maps and time-series plots. The maps, however, are only used for the most recent period (1901–2000) due to the limited number of stations in earlier periods. For each period, seasonal indices starting with spring (MAM) and ending with winter (DJF) are presented. The order of presentation is Tmin/Tmax, followed by Tmean and Precipitation (see Table 2.2). To make it easier to find an index in a given season and for a given period, a header is put on each page to indicate the period, season, and index group. The circles in the maps indicate station locations for the two longer periods where results for individual stations are presented. All the maps contain a colour bar symmetric around zero and a title (Fig. 3.1). The range is determined by the highest absolute value appearing in the map. An index dependent general colour scheme is used throughout the whole atlas. For temperature indices, the colour scale ranges blue-green-red where red colours indicate warming and blue colours cooling conditions. For example, an increase in Tmean would be shown in red as well as a decreased number of days below the second percentile. Trends in precipitation indices are visualized using a brown-yellow-green colour scale where brownish colour indicate drier and greenish colours wetter conditions. Trend significance is indicated for each symbol marking a station (circles) or regional averages (squares) using significance levels of $p < 0.05$ and $p < 0.01$. Analysis period, season, index and the unit of the trend are provided in every figure title.

For the time-series plots, each individual station's data are separately shown for the two longer periods (1801–2000 and 1851–2000), while the regional means are displayed for the period 1901–2000 on background plots containing all contributing individual station time series (in light grey lines). Each figure shows annual values of an index for a season, its low-frequency variation and long-term linear trend (Fig. 3.2). The smoothed curve emphasizing low-frequency variation is a 10-year Gaussian filter applied to the original time-series suppressing variations on time-scales less than 10 years. The straight solid line shows the linear trend estimated by linear regression for the period in question. The statistical trend significance is indicated as follows: '*' significant at $p < 0.05$, '**' significant at $p < 0.01$, and '()' not significant. In each figure analysis period, the names of stations or region, season, index name and trend unit are indicated. To save space, two (and sometimes three) indices or two trend lines for two periods are plotted in the same figure whenever appropriate and feasible (Figs. 3.3, 3.4, 3.5, 3.6, 3.7, 3.8, 3.9, 3.10, 3.11, 3.12, 3.13, 3.14, 3.15, 3.16, 3.17, 3.18, 3.19, 3.20, 3.21, 3.22, 3.23, 3.24, 3.25, 3.26, 3.27, 3.28, 3.29, 3.30, 3.31, 3.32, 3.33, 3.34, 3.35, 3.36, 3.37, 3.38, 3.39, 3.40, 3.41, 3.42, 3.43, 3.44, 3.45, 3.46, 3.47, 3.48, 3.49, 3.50, 3.51, 3.52, 3.53, 3.54, 3.55, 3.56, 3.57, 3.58, 3.59, 3.60, 3.61, 3.62, 3.63, 3.64, 3.65, 3.66, 3.67, 3.68, 3.69, 3.70, 3.71, 3.72, 3.73, 3.74, 3.75, 3.76, 3.77, 3.78, 3.79, 3.80, 3.81, 3.82, 3.83, 3.84, 3.85, 3.86, 3.87, 3.88, 3.89, 3.90, 3.91, 3.92, 3.93, 3.94, 3.95, 3.96, 3.97, 3.98, 3.99, 3.100, 3.101, 3.102, 3.103, 3.104, 3.105, 3.106, 3.107, 3.108, 3.109, 3.110, 3.111, 3.112, 3.113, 3.114, 3.115, 3.116, 3.117, 3.118, 3.119, 3.120, 3.121, 3.122, 3.123, 3.124, 3.125, 3.126, 3.127, 3.128, 3.129, 3.130, 3.131, 3.132, 3.133, 3.134, 3.135, 3.136, 3.137, 3.138, 3.139, 3.140, 3.141, 3.142, 3.143, 3.144, 3.145, 3.146, 3.147, 3.148, 3.149, 3.150, 3.151, 3.152, 3.153, 3.154, 3.155, 3.156).

D. Chen et al., *European Trend Atlas of Extreme Temperature and Precipitation Records,* DOI 10.1007/978-94-017-9312-4_3

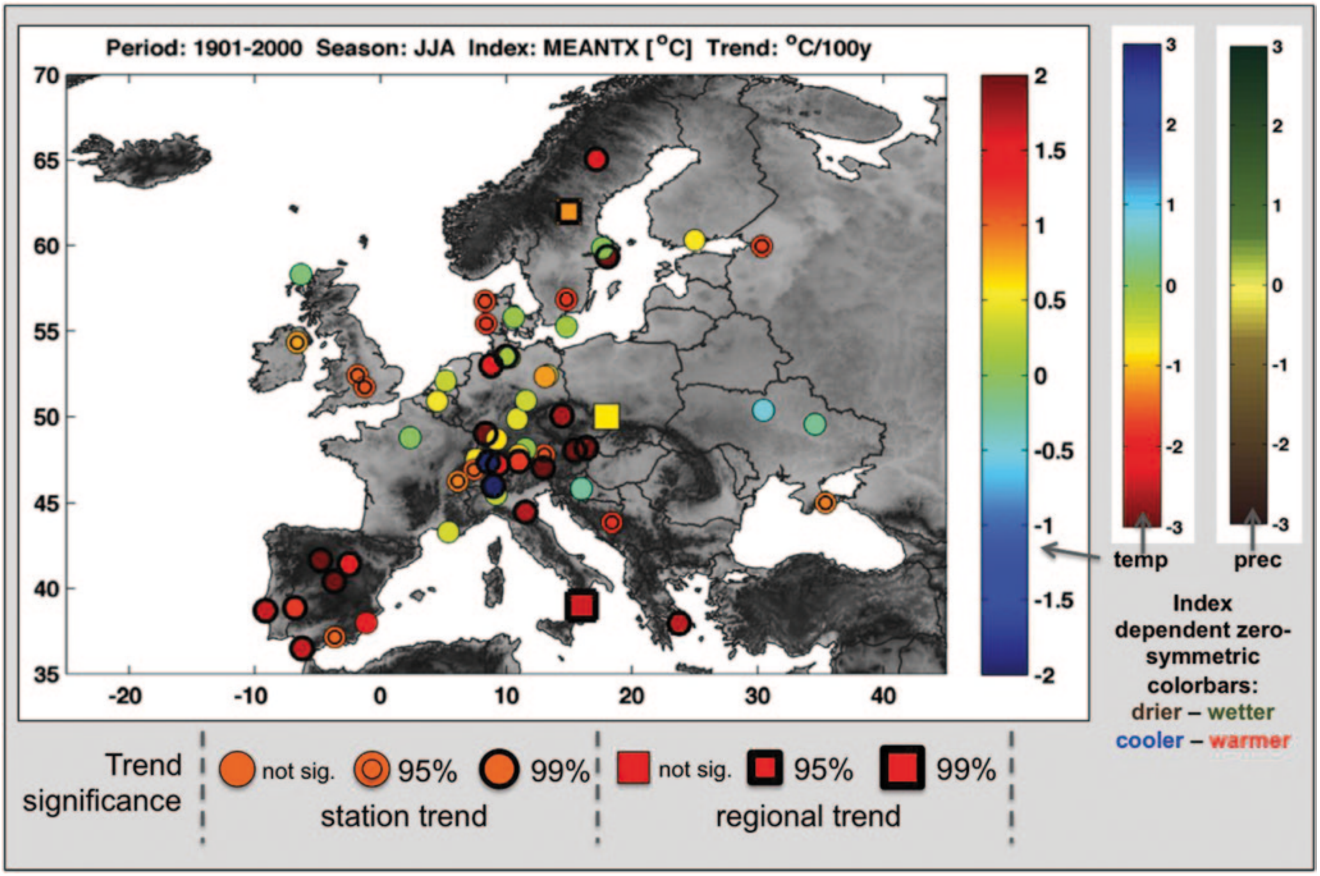

**Fig. 3.1** Map layout and legend used throughout the atlas. Color scales change depending on the index

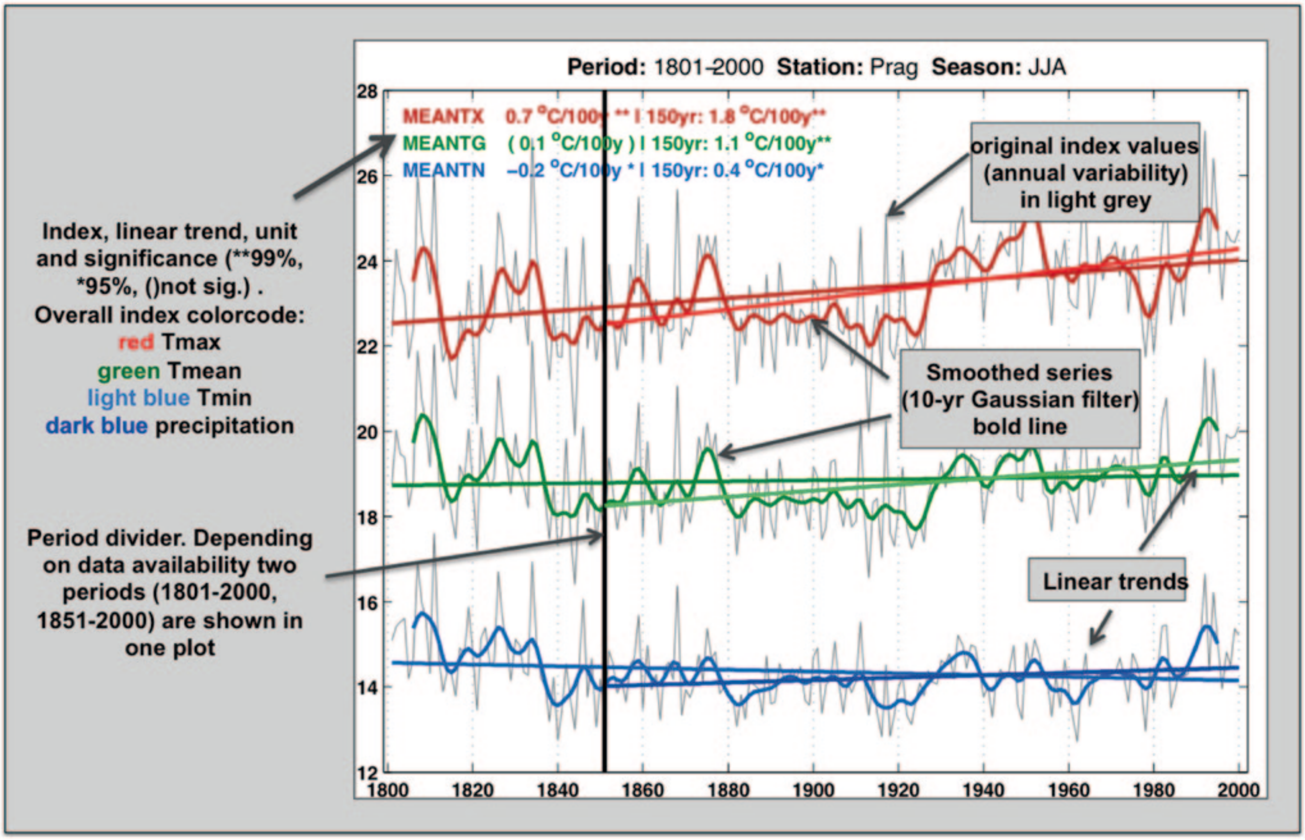

**Fig. 3.2** Layout and legend for the time-series plots

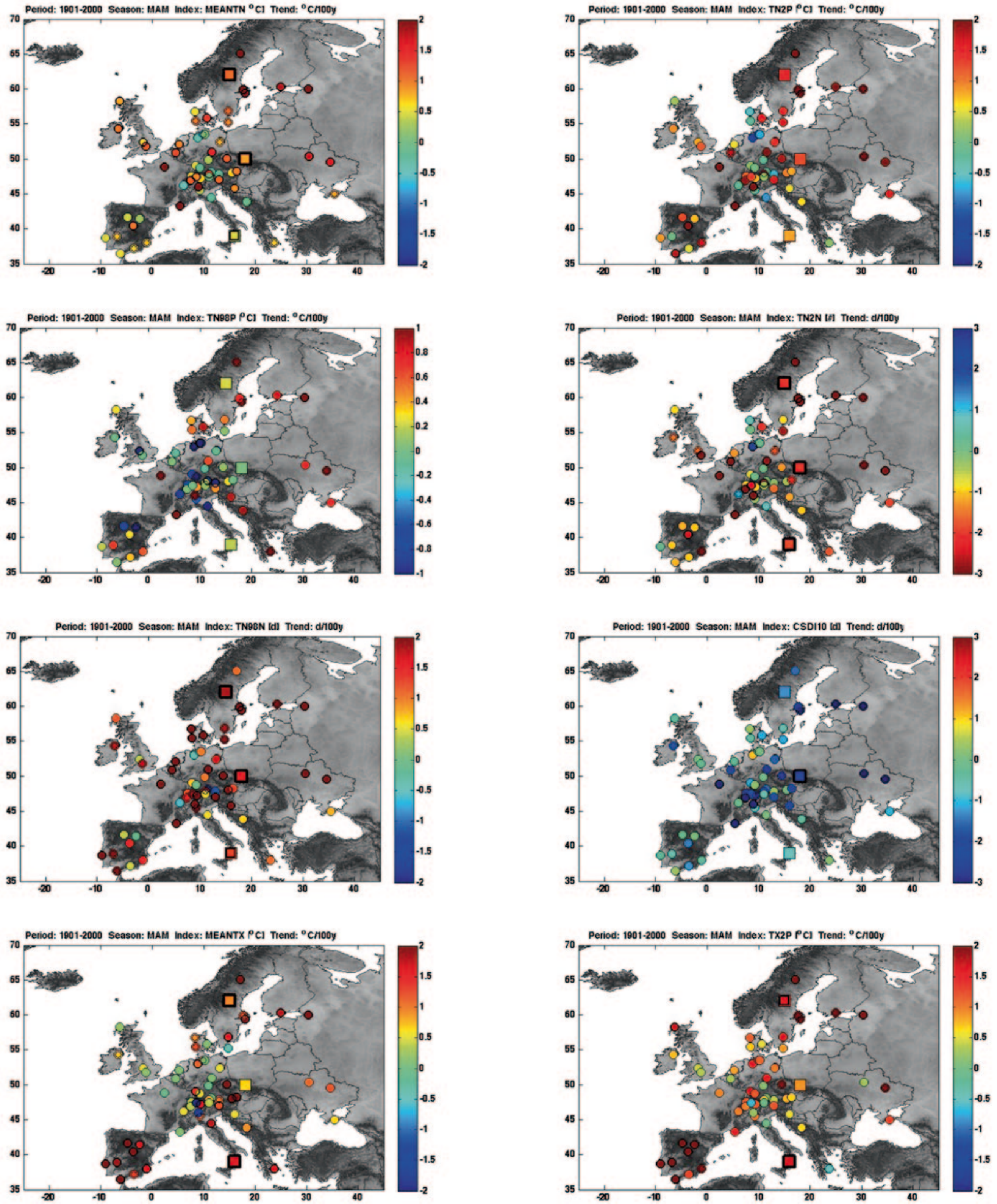

**Fig. 3.3** 1901–2000 MAM Tmin